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National Aeronautics & Space Administration
Washington 25, D.C.

ATTN: Messrs Alfred Gessow, Mark Heidmann
Dr. Robert Levine and Dr. Richard Priem

SUBJECT: NASA Contract NASr-217, Quarterly Status Report for the period 1 June 1966 through 31 August 1966.

Gentlemen:

[illegible] This informal three-month status report covers the recent research activities [illegible] "Nonlinear Aspects of Combustion Instability in Liquid Propellant Rock[illegible])

[illegible] various interrelated phases of this research are listed in the order indicated in the work statement associated with Contract NASr-217.

I. Stability-Limits Testing

The initial tests are now in progress utilizing the acoustic liner chamber section. Pressure checkout following Nicro brazing of the 53* individual, adjustable volume resonating chambers indicated zero leakage. The key to the adjustable volume feature, the Teflon and stainless steel "TRUSEAL", was found to leak at rates which have proven to be no problem in the hot firings.

Three chambers have been fitted with flush-mounted Kistler transducers to determine optimum resonator chamber length. The basis for the choice will rest on the maximum pk-pk pressure measurements recorded. Several tests are anticipated in this initial series prior to operation with all chambers in the optimum damping configuration. Measurements within the cavities will also seek to establish the type of flow present in the orifices, i.e., jet-type, choked, etc., and the temperature environment.

The injector initially being used in these tests, a 16-spud like-on like element design, has a well-established instability behavior over a range of pulse gun disturbances (50 to 300 psi pk-pk initial amplitudes). Based on this, comparisons will be made as to the effectiveness of the resonating chambers to damp disturbances over this range of initial disturbances.

Future tests with unlike type impinging spud designs, which in previous Princeton tests have been spontaneously unstable, are planned to further explore the damping capabilities of the acoustic liner. In both the present and future tests location of active resonators and the resultant effect on damping will be investigated.

The first step in the attempt to find a theoretical description of the performance of an acoustical liner in a rocket combustion chamber was to

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* The final fabricated design required that seven resonating chambers be eliminated (nominal 60) because of leak problems with the copper weld and transducer, TEAL jet and pressure tap locations.

deal with a single cavity in the presence of a simple pressure oscillation. The losses occurring in an acoustic cavity when an external pressure oscillation is imposed upon it have been found to be very nonlinear due to their heavy dependence on the kinetic energy of the jet. The differential equations describing the response of the cavity are therefore not treatable analytically when the amplitude is large. Therefore, it has been the object to numerically integrate a set of differential equations which describe the nonlinear situation. Numerical treatment of the equations in a meaningful fashion is made possible only by the use of a high speed computer.

Since there is an infinite variety of possible combinations of the various parameters involved, it was decided to use values which pertain to a forthcoming experiment with an acoustic liner here at Princeton. The chamber pressure oscillations were chosen to be sinusoidal in the initial attempt. To help in interpreting the results the wave form of the oscillations are being plotted. This should prove useful since the cavity response deviates somewhat from a purely sinusoidal oscillation. In addition other parameters such as phase angle and pressure amplitude are being plotted as functions of chamber oscillation frequency. It is hoped that a meaningful comparison of these results can be made with the linearized theory as presented in the Sixth Yearly Progress Report.

II. Nonlinear Displacement Studies

The following is the summary of a report in preparation involving experimental research related to nonlinear displacement. The work was performed by J. A. Newman.

"An experiment has been performed to investigate the breakup of a vaporizing liquid jet. Its behavior has been studied under a variety of steady and oscillatory pressures.

It has been observed that chamber pressure has no significant effect on jet length in the laminar regime so long as the fluid is not rapidly evaporating. For the fluid whose vaporization rate is substantial, a decrease in chamber pressure and the subsequent increase in vaporization, leads to a slight decrease in jet length. This effect becomes more pronounced the larger the jet diameter. In the turbulent region the effect of pressure depends on the fluid under observation, the jet velocity and jet diameter. For a very slowly evaporating fluid, chamber pressure always accelerates jet breakup. This can be attributed to the increased effect of air friction. The length of a vaporizing Freon jet, however, sometimes decreases with chamber pressure and under other circumstances increases. Generally the evaporation process becomes more important than air friction in controlling jet length when the jet diameter is large and jet velocity is high.

When the gas in the chamber is subjected to acoustic oscillations, jet breakup is generally enhanced regardless of whether the fluid is rapidly evaporating or not. The effect, though, is only measurable in the laminar regime. At low steady-state chamber pressures, oscillatory pressure (standing mode pressure antinode) and oscillatory velocity are both about as effective in promoting the breakup of a non-evaporating fluid. At higher steady pressure levels, pressure oscillations (standing mode pressure antinode and spinning mode) are more effective than velocity oscillations. The behavior of a vaporizing fluid is essentially the same as a non-vaporizing fluid except that velocity oscillations become as effective as pressure oscillations at high chamber pressure. As chamber pressure is lowered and vaporization rates increase, velocity oscillations become more effective than pressure oscillations.

Under none of the circumstances encountered in the experiment, did the spinning mode enhance jet breakup to a greater extent than the standing mode."

Photographic studies using a window port to observe the velocity conditions within a 9-inch diameter rocket thrust chamber have shown the following: no [illegible] motion in the tangential direction is present with 100 [illegible] instability and significant changes in the burning [illegible] is present [illegible] show[illegible]

III. [illegible]

The theory and results of the nozzle admittance calculations are still in the final stages of preparation for publication.

IV. Nonlinear Transverse and Longitudinal Studies

The difference equations for transverse wave motion in a cylindrical chamber have been programmed for the IBM 7094 computer. A frame of reference which rotates with the wave has been employed in order to reduce the integration time. Both annular and full chamber geometries have been considered. In the initial phase, the initial conditions will have a functional form given by the linear solution with the amplitude as an arbitrary input parameter. It will be interesting to see whether the nonlinear periodic solution which develops after some time (theoretically this is infinite, but practically it will be finite) will contain a shock wave or will be of the form predicted by Maslen and Moore.

As was stated in the yearly report, analytical solution of the equations describing the pressure wave form occurring when shock waves are present in the longitudinal mode is possible for only one value of the interaction index, namely $n \to \infty$. (An anlytical solution is also possible when $n = n_0$, this being the trivial case of zero amplitude at the stability limit.) It is highly desirable to find the wave shapes for other values of n, not only for the obvious purpose of determining the dependence of the wave shape on the displacement from the linear stability limit but also to find the approximate dependence of ϵ, the shock amplitude, on this displacement. As given in the yearly report the amplitude is represented by $\epsilon = MH(n - n_0)$, where $H(n - n_0)$ is the function to be determined through numerical investigation.

During the period covered by this report one numerical method for integrating the pertinent equations was conceived, underwent a gestation period of "debugging" and alteration and finally bore some interesting and satisfying results.

First of all, the numerical results verify the predictions of the wave form inferred from a topological analysis for the particular case $n = \frac{\gamma + 1}{2}$ (γ being the ratio of specific heats) as given in the yearly report. These predictions were that the solution would have zero slope immediately before and following the shock and infinite slope one-half period following the shock. This was precisely what the numerical results showed. In fact an infinite slope at a time one half period after the shock was found to be present for all values of n investigated.

Secondly, the numerical results show that a strong tendency exists for the wave form to become sinusoidal in shape as the stability limit is approached. This is of course very encouraging as it indicates a convergence between the present nonlinear analysis using ϵ of the order of the Mach number and the original linear work which took ϵ small compared with Mach number. At large distances from the stability limit, the slope of the pressure wave immediately before the shock is negative and becomes more negative as n is increased. This can be interpreted as a tendency toward a sawtooth and away from sine wave as n is increased.

Finally the approximate form of the function $H(n - n_0)$ can be deduced from numerical data. The function appears to be approximated to a good degree of accuracy by the linear relationship $H(n - n_0) = 2.93\ (n - n_0)$.

In summation, the numerical results indicate that for the case of shock-wave instability where a time lag equal to one-half of the period is present (the resonant case) the wave form of the solution tends toward the linear solution at the linear stability limit and toward a more sawtooth form far from the stability limit and that the amplitude parameter, ϵ, can be represented with good accuracy as $\epsilon = M \times 2.93(n - n_0)$ where M is the Mach number.

V. Start Transients

Initial attempts to analytically treat the problem did not lead to meaningful results. Before a fruitful approach to the problem could be developed, the graduate student conducting the research transferred to another project. Therefore, the start transient studies have been inactive since last March. The renewal will be considered with the arrival of new graduate students this month.

VI. Higher Mach Numbers

The reactivation of this project will also be considered with the arrival of new students this month.

VII. Droplet Wake Studies

The linear analysis of droplet evaporation under oscillatory field conditions is still under way. Three simultaneous first-order linear differential equations have been derived on the basis of small perturbations. The problem arises from the couplings of three unknowns; perturbations of droplet velocity, temperature and mass, and also from the singular behavior of the equations at the point where $\overline{\Delta v}$ (the difference of mean gas and droplet velocities) goes to zero. A numerical method has been studied by simply omitting the singular terms in the neighborhood of the singular point. The reason is based on the physical argument that the singularity could not exist and the relation

$$Nu = 2.0 + 0.6\, Sc^{1/3}\, Re^{1/2}$$

is questionable in the vicinity of $Re = 0$ for the unsteady case. So far, no strong evidence supports such an argument.

In order to take a better look at the singular point, series expansions in the power of $|\overline{\Delta v}|^{\frac{1}{2}}$ are carried out in the region where $\overline{\Delta v} \approx 0$. In the transverse case we have

$$\frac{u_1}{\bar{u}} = c_{10}$$

$$\frac{T_{\ell 1}}{\bar{T}_{\ell}} = c_{20} + c_{21}\, |\overline{\Delta v}|^{\frac{1}{2}} + c_{22}\, |\overline{\Delta v}|$$

$$\frac{m_1}{\bar{m}} = c_{30} + c_{31}\, |\overline{\Delta v}|^{\frac{1}{2}}$$

u_1, T_1, m_1 are perturbation quantities of droplet velocity, temperature and mass, respectively. c_{10}...., c_{31}.... are functions of local conditions and are considered as constants. We see that all the perturbations approach finite values which depend upon local conditions at the singular point. Therefore, the technique employed in the numerical integration seems to be applicable.

VIII. Droplet Population Studies

Experimental data relating chamber pressure to droplet population wave frequency were presented in the annual report. Correlation between water and water-alcohol mixtures in cold flow and hot firings of LOX/ALC in 9-inch diameter chambers was also shown. Following this work an effort was made to lessen the data reduction difficulties via use of photocells with frequency analysis performed with the aid of IBM 1620 equipment. Based upon the test analyzed such approaches may eventually offer the sought-after improvements, however, the present method involving streak camera photography and subsequent hand analysis remains the most reliable. In the past weeks a number of new records have been obtained of tests utilizing surface tension reducing additives. Results are expected in the next few weeks.

IX. Early Combustion Behavior

As discussed in the yearly status report, work on the chemical kinetic apparatus awaits a new undergraduate this fall. A brief report by the previous undergraduate student points out the necessary compromises that were required to match the 210^{o}F maximum temperature of the vaporizer. Plans are underway to increase this capability to 400-500^{o}F by the first of the year. Based on the previous limitations, $C_{10}H_{20}$ hydrocarbons (representing RP-1) could not be tested and instead interest was centered on pentane. Even with pentane oxidation was not completed entirely within the duct and hence iso-pentane received the most extensive study. Both pentane-types exhibited sizable ignition delays with the iso-pentane ignition delay time (physical and chemical) being approximately 105 milliseconds for the duct near ambient pressure. Ethyl alcohol, on the other hand, indicated a reaction immediately following injection.

Also associated with the early combustion behavior is the mixing of the [illegible] droplets. In the case of the injectors used on the square-motor hardware, the 4 x 4 grid provides a 0.67 inch spacing between opposite propellant sprays. The degree of mixing as one moves from the injector face is measured with a collection apparatus which provides both mass and mixture ratio information. However, such measurements are only at 1/2 inch intervals using 1/4 inch diameter collector tubes. For this reason the multiple thermocouple probe has been used with the RP-1 at 80^{o}F and ethylene glycol (pseudo LOX) at 185^{o}F . This approach provides continuous mixture ratio across the injector. Comparisons between the two methods have been quite good especially in the center of the injector (errors of approximately $\pm$ 15%). Because of mixture ratio gradients which are often quite severe the thermocouple probe data appears to be more representative of the conditions prevailing. Probing at 7 inches indicates a relatively flat mixture ratio close to the design mixture ratio of 2.2 while at 3 inches the effect of each propellant fan is very evident. The undergraduate student who has been working on these surveys for the past few months is currently filling in data involving surveys closer to the injector face as well as intermediate locations. Next week 6 x 6 grids will be probed with a characteristic .44 inch spacing. It is realized that in the absence of gas recirculation and combustion such cold flow tests cannot accurately represent the environment of actual firings. However, it is hoped that comparisons with velocity and combustion profile data will place the mixing process for like-on-like patterns in proper perspective.

X. Property Measurements in Rocket Motors

In a continuation of the study of energy balances based on wave strength at various axial stations in the square-motor, tests have focused most recently on the nozzle-end. Over the range of chamber pressures (300-900 psia) and subsonic Mach numbers (.05 to .3) tested it was found that a sizeable fraction of the incident wave amplitude is absorbed at the nozzle-end. Hence the reflected wave rather than having an amplitude twice that associated with a single wave at midlength (the point at which the amplitude of the moving wave front can be most accurately gauged since incident and reflected waves are 180° out of phase) has a value between 1.2 to 1.6 depending on the chamber environment. Higher pressures and lower subsonic Mach number (higher contraction ratio) fall at the 1.6 end of the scale. Although trends are indicated in these results certain problems of data recording (overshoot of the signal associated with the shock-type wave and frequency limits of the recording system) tend to limit the quantitative content.

Because of these shortcomings further testing will be limited until: 1) new recording capabilities are available in the form of the Honeywell 7600 tape recorder (expected later this fall), 2) a new Ph.D. candidate arrives (expected within the next week) and 3) final evaluations are completed on the rocket hardware to further determine transducer capabilities (these tests are in progress).

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